HEAT LOSS FROM HUMAN BODY AND INSULATION
VALUE OF CLOTHING ENSEMBLE

by

HUNG CHEUNG LEUNG

B. Sc., Chu Hai College, 1964

A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1968

Approved by:

Major Professor

TABLE OF CONTENTS

NOMENCLATURE

a - p - Temperature readings of 16 thermocouples on manikin surface

A - Area, ft^2

A_{Du} - Body nude surface area measured by DuBois method, ft^2

C - Rate of convective heat loss to air, Btu/hr

C_p - Specific heat at constant pressure of the fluid, Btu/lb-F

D - Heat loss by skin diffusion, Kcal/hr

D - Diameter of cylinder similated to human body, ft

E - Rate of heat loss by evaporation, Btu/hr

f_{clo} - Ratio of the clothing surface area to DuBois area

F_{eff} - Ratio of the effective radiation area of the clothing surface to the surface area of the clothed body

g - Acceleration due to gravity, ft/hr^2

h_c - Convective heat transfer coefficient, Btu/hr-ft^2-F

h_r - Radiative heat transfer coefficient, Btu/hr-ft^2-F

H - Total sensible heat loss from the body = C + R, Btu/hr

K - Rate of conductive heat exchange with the subject contact on the body, Btu/hr

k - Conductivity of the air entrapped by clothing, Btu/hr-ft^2-ft-F

M - Rate of body heat production, Btu/hr

P - Atmosphere pressure, lb/in^2

P - Partial vapor pressure in air, Hg mm

P - Power input to copper manikin, Watt

r - Heat of vaporization of water at 35°C

R_e - Reynolds number = $\underline{DV}$

R - Rate of radiation heat loss to surroundings, Btu/hr

R - Thermal insulation, Clo (See page24, table 4 and fig. 5)

R_w - Latentrespiratory heat loss, Kcal/hr

$\overline{S}$ - Rate of change of heat storage in the body, Btu/hr

t - temperature, F

T - Absolute temperature, R

V - Air velocity, ft/min

W - Rate of work done, Btu/hr

W_{ex} - Humidity ratio of the expiration air, lb_w/lb_a

W_a - Humidity ratio of the air intake, lb_w/lb_a

σ - Stefan Boltzmann contant - 0.1714 10^{-8} Btu/hr-ft^2-R^4

ε - Emissivity

β - Coefficient of volumetric expansion, F

ρ - density of the fluid, lb/ft^3

μ - viscosity of the fluid, lb/hr-ft

Subscripts

a - Air

b - surface of the manikin

clo - surface of the clothing

enc - enclosure

w - wall

' - applied on R, means total insulation

$\overline{R}$ - applied on R, means insulation averaged on the whole body surface

INTRODUCTION

Men are continuously searching for a way to protect themselves from an unfavorable atmosphere and create a more favorable environment for both comfort and convenience. Clothing plays a very important part in human comfort, and consequently it has been the subject of intense research.

There has been a large amount of research done on human comfort with different temperatures, humidities and body activities. Most of these works have been done at extremes of environmental conditions. (1, 2, 3, 4)*

Thermal comfort studies with human subjects and civilian clothing as worn by the general public under climatic conditions commonly encountered are limited (5, 6, 7, 8, 9, 10). Some of the recent works on human comfort have been described by Nevins (11), Nevins <u>et al</u> (12), and McNall <u>et al</u> (13).

Most of the above mentioned works used the method keeping the clothing worn by the subjects constant and allowing some of the other factors such as air temperature, air humidity, air velocity, wall temperature, body activities and exposure time, which influence thermal comfort to vary. Little research was found reporting studies of the amount of the thermal insulative value of men's garments.

The purposes of this study were:

---

*Bibliography is listed on page 40

1. To find the amount of clothing required for human comfort at various air temperatures and body activities.
2. To measure the sensible heat loss from the nude body and compare these results of sensible heat loss, from the copper manikin surface with the previous literature.
3. To analyze the additive effect of the combinations of several clothing layers.

CHAPTER I

THERMAL EXCHANGES OF THE HUMAN BODY WITH THE ENVIRONMENT

Body temperature depends upon the balance between heat production and heat loss. Heat resulting from oxidation of food elements in the body (metabolism) maintains the body temperature well above that of the surrounding air in a cool environment. At the same time, heat is constantly lost from the body by radiation, convection, conduction and evaporation.

According to the first law of thermodynamics, evergy input should equal energy output plus change of the energy within the body. Thus, heat exchanges between the body and its environment may be generally expressed as:

$$M = \pm S \pm E \pm R \pm C \pm W \pm K \quad (Btu/hr) \tag{1}$$

where

M = rate of body heat production by metabolism (Btu/hr)

S = rate of change of heat stored in the body (Btu/hr)

E = rate of heat loss by evaporation (Btu/hr)

C = rate of convective heat exchange with air (Btu/hr)

R = rate of radiation heat exchange with surrounding surfaces (Btu/hr)

W = rate of work done by the body (Btu/hr)

K = rate of conductive heat exchange with surfaces in contact with the body (Btu/hr)

Metabolism

The rate of metabolism is largely dependent upon muscular activity and may vary from less than 400 Btu/hr for an adult seated at rest to more than 2500 Btu/hr. for subjects doing heavy work (14). Even at the same activity, the rate of metabolism varies with the environmental temperature, especially when the body is in the zone of metabolic regulation against cold. In this zone, heat production rate is increased by body shivering (14).

When a copper manikin is used to similate the human body, heating elements consisting of flexible resistance wires are sewn to thin cloth cemented to the inside of the copper shell. The resistance can be adjusted to similate different heat production rates over the body surface area and the voltage can be adjusted to similate different body activities or desired temperature differences when air temperature is constant.

Radiation

Radiative heat exchange occurs when the mean radiant temperature (MRT) is different from the clothing surface temperature (or mean body surface temperature when nude). Radiative heat exchange can be expressed as follows (15):

$$R = \frac{f_{eff}\, f_{clo}\, A_{Du}\, \sigma\, (T_{clo}^4 - T_{mrt}^4)}{\frac{1}{\mathcal{E}_{cl}} + \frac{A_{Du}\, f_{clo}\, f_{eff}}{A_{enc}} \left[\frac{1}{\mathcal{E}_{enc}} - 1\right]} \qquad \text{(Btu/hr)}$$

Where

f_{eff} = ratio of the effective radiation area of the clothed body to the surface area of the clothed body.

f_{clo} = ratio of the clothing surface area to DuBois area.

σ = 0.1714×10^{-8} Btu/hr-ft^2 Stefan-Boltzmann constant

A_{Du} = manikin's surface area by DuBois' method (34)

T_{mrt} = absolute mean radiant temperature (R)

T_{cl} = absolute temperature of the clothing surface (R)

$\mathcal{E}_{cl}$ = emissivity of the outer surface of the clothing (or skin surface when it is nude)

$\mathcal{E}_{enc}$ = emissivity of the enclosure surface

A_{enc} = area of the enclosure surface (ft^2)

If the ratio $\frac{A_{Du}\, f_{eff}\, f_{clo}}{A_{enc}}$ is relatively small, or the surface of the enclosure is nearly black, as it normally is, Eqn. 2 reduced to

$$R = f_{eff}\, f_{cl}\, A_{Du}\, \sigma \mathcal{E}_{cl} \quad (T^4_{clo} - T^4_{mrt}) \qquad \text{(Btu/hr)} \qquad (3)$$

Fig. 1 shows a composite of data from many authors for the reflectance in the visible and near infrared regions for a white and a dark skin. The major differences in reflecting power are in the visible and near infrared range. If the skin temperature is 91.5°F, by Planck's distribution function (16), about 95% of the heat is admitted at the wavelengths greater than 0.01 μ. In this range, the reflectance of human is quite constant from 0.01 to 0.015 (see Fig. 1).

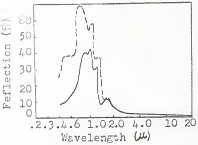

Fig. 1 Reflecting Power of Human Skin (14)

The effective radiation area is less than DuBois area because the parts between arms and between legs partially radiate to each other. The effective radiation area is 65% when sitting and 75% when standing as recommended by Fanger (17).

Thus, for a standing man, Eqn. 3 can be reduced to

$$R = 0.125\left[(T_{cl}/100)^4 - (T_{enc}/100)^4\right] \quad \text{(Btu/hr)}$$

or

$$R = h_r(t_{cl} - t_{enc}) \quad \text{(Btu/hr)} \qquad (4)$$

where h_r is a function of wall and body surface temperature only. If the wall temperature is fixed (70°F) as in this case, h_r is a function of body temperature only and is listed in Table 1.

Table 1. Radiative Heat Transfer Coefficient

$t_b - t_w$	1	25	50	75	100
h_r (Btu/hr-ft^2-F)	.745	.796	.819	.860	.900

To facilitate the calculations, a suggestion is made that the radiative heat transfer coefficient be considered constant over the practical experimental range of temperature difference. The error due to this suggestion is only 3% if temperature differences are in the ranges from 1 to 15°F. This suggestion is followed through out this paper.

Convection

The basic equation for convection heat transfer is

$$C = h_c A_{clo} (t_{clo} - t_a) \qquad \text{(Btu/hr)} \qquad (5)$$

where

h_c = convection heat loss coefficient (Btu/hr-ft^2-F)

t_a = air temperature (F)

A_{cl} = area of clothing surface (or A_{Du} when nude) (ft^2)

A_{cl}, t_{cl} and t_a can be measured directly, h_c can be expressed as

$$h_c = f(D, V, \mu, \rho, \Delta t, K, C_p, g, \beta, P)$$

where

D = characteristic geometrical dimension (ft)

V = velocity of fluid (ft/min)

μ = viscosity of the fluid (lb/hr-ft)

ρ = density of the fluid (lb/ft^3)

Δt = temperature difference between body surface and ambient fluid (F)

K = thermal conductivity of the fluid (Btu/hr-ft-F)

c_p = specific heat at constant pressure of the fluid (Btu/lb-F)

g = acceleration due to gravity (ft/hr^2)

β = coefficient of volumetric expansion (F)

P = pressure of atmosphere (Psi)

Convective heat transfer can be divided into two types: forced convection and free (natural) convection depending upon the velocity of the fluid and the temperature difference.

Forced Convection

Forced convection is usually considered to be that which occures when the body is placed in a moving fluid influenced by some external forces.

Many investigators attempted to solve this problem both theoretically and experimentally. The following is some of their works, Buttner (18), for V 0.2 m/sec.

$$h_c = \frac{0.70}{D} Re^{.52} \qquad (Cal/m^2\text{-min-C})$$

where

$$Re = \text{Reynolds number} = \frac{DV\rho}{\mu}$$

Winslow et al (19)

$$h_c = 10.4\ V^{\frac{1}{2}} \qquad (Kcal/m^2\text{-hr-C}) \tag{7}$$

where

V = air velocity (m/sec)

McNall and Sutton (20) applied a basic heat transfer equation for a cylinder to the human body, approximating it as a vertical cylinder 68" in hight and 19.5 ft^2 in area on the recommendation of the ASHVE GUIDE (21)

$$h_c = 0.057\ V^{.56} \qquad (Btu/hr\text{-}ft^2\text{-}F) \tag{8}$$

where

V = air velocity (ft/min)

Free (natural) Convection

Free convection heat transfer occurs whenever a body is placed in a fluid at higher or lower temperature than that of the body. As a result of the temperature difference heat flows between the fluid and the body causing a change in the density of the fluid layers in the vicinity of the surface. The difference in density leads to a downward flow of the heavier fluid and an upward flow of the lighter fluid and heat transfer occures associated with this fluid flow.

Nielsen and Pedersen (22) recommended the following equation for both men sitting and standing,

$$h_c = 2.05\ (t_b - t_a)^{0.25} \qquad (Kca\ l/m^2\text{-}hr\text{-}c)$$

McNall and Sutton based on the same cylinder mentioned above recommended

$$h_c = k_1\ (t_b - t_a)^{.25} \qquad (Btu/hr\text{-}ft^2\text{-}F)$$

Where

k_i = constant, depending on the temperature range

= 0.0269 in this case

t_b = nude body (of clothing) surface temperature

One must decide whether forced or free convection preveiles when both temperature difference and air flow occur. Undoubtedly there will exist a zone where the influence of both temperature difference and velocity of fluid are of same order of manitude. It is proposed to use the usual rule for the calculation of convective heat transfer in this zone. This is to calculate h_c for both free and forced convection and use the larger value of the two.

Fanger (17) proposed to use equation 9 for free convection and equation 7 for forced convection.

McNall et al (20) proposed to use equation 10 for free convection and equation 8 for forced convection.

The results for both proposals were plotted in Fig. 9 where air velocity is assumed constant (30 ft/min).

Conductive Heat Transfer K

Thermal conduction is a transportation of energy due to moleclar motion. For the purposes of this study, conductive heat transfer was considered to be that associated with the heat exchange between two intimately touching solid objects. In the case of a man standing on the floor, conductive heat transfer is very small, and can be neglected (only the small areas of feet are in direct contact on the floor).

<u>Evaporation</u>

The phenomenon of evaporative heat loss can be broken up into three parts; skin diffusion, latent respiration and sweat secretion.

Skin diffusion, which is a function of body skin temperature and vapor pressure in the air, is water vapor diffused through human skin. Fanger (17) suggested the following equation based on data by Inouye <u>et al</u> (23)

$$D = 0.35\, A_{Du}\, (P_b - P_a) \qquad \text{(Kcal/hr)} \tag{11}$$

where

P_b = saturated water vapor partial pressure at body skin temperature (mm Hg)

P_a = partial pressure of water in the surrounding air (mm Hg)

Latent respiration heat loss occurs from the transfer of water vapor to the inspired air from the mucosal surface. Fanger (22) has reported that latent respiration heat loss is a function of the pulmonarary ventilation and the difference in water content between expired and inspired air:

$$R_w = V\, (W_{ex} - W_a)\, r \qquad \text{(Kcal/hr)} \tag{12}$$

where

R_w = latent respiration heat loss (Kcal/hr)

V = pulmonaty ventilation (Kg/hr)

W_{ex} = humidity ratio of the expiration air (Kg water/Kg dry air)

r = 575 Kcal/Kg = heat of vaporization of water at 35°C.

Sweat secretion is more difficult to define and express mathematically since it is physiologically controlled. In the thermal comfort range McNall et al (13) found experimentally that for college males and females, the total evaporative heat loss is a function of metabolic rate and the body surface area and could be expressed as follows:

$$\frac{E}{A_{Du}} = .512 \frac{M}{A_{Du}} - 11.7 \quad (\text{Kcal/m}^2\text{-hr}) \quad (\text{at } 45\% \text{ RH}) \qquad (13)$$

By making use of equations 11, 12 and 13, the heat loss by sweat secretion can be expressed by

$$\frac{\overline{S}}{A_{Du}} = 0.42 \left(\frac{M}{A_{Du}} - 50\right) \quad (\text{Kcal/hr}) \qquad (14)$$

The above discussion for evaporative loss from body applies under comfort conditions. Winslow and Herrington (23) reported that when the air temperature is above a certain point sweat secretion increases sharply with an increase in air and wall temperature and bears no relation to the relative humidity of the atmosphere.

The evaporation is driven by the difference of vapor pressure at the skin and vapor pressure in the environment and may be described by the following equation if the body is completely covered by liquid (24) (The body area is taken for the average adult)

$$E = 517\ V^{.4}\ (P_b - P_a) \qquad \text{(Btu/hr)} \qquad (15)$$

where

V = air velocity (ft/min)

P_b = pressure of saturated water vapor, at the body surface temperature (Psia)

P_a = water vapor pressure in air (Psia)

However, the body surface is not always covered wholly with liquid. A wetted area concept is introduced and defined by

$$W.A. = E/E'$$

where

E' = theoretically attainable evaporative heat loss if the body is completely covered with moisture and it can be calculated by equation 15

From Eqn. 1 with a fixed metabolic rate, air and wall temperature, air velocity (M, R, C constant) E is the only term left. Thus, it is fixed if the body is in equilibrium with the environment ($S = 0$). By varying W.A. the body is able to maintain thermal equilibrium over a range of environments with resonable variations of body temperature which will not impare the vital organs.

There are two upper limits for evaporative heat regulation under extremely hot conditions.

1. The amount of moisture which the atmosphere can actually absorb from the total saturated surface area as calculated from eqn 15. This limit can be increased by increasing the air velocity.
2. It is believed that the sweat rate should not exceed one litre per hour (2400 Btu/hr) for reasonable periods or the body will suffer from excessive water and sodium chloride losses (24).

The actual latent heat loss could be measured by the measured weight loss times the latent heat of vaporization taken at the average skin temperature for a nude subject. However, for a clothed body, there are three paths by which the evaporation process may take place: water may evaporate from the skin and diffuse through the clothing; water may wet the clothing and then evaporate at the clothing temperature; or the moisture may be evaporated from the skin, condense on the clothing and then reevaporate at the clothing temperature, the latent heat of vaporization is therefore difficult to establish accurately.

CHAPTER II

CLOTHING AND COMFORT

General

The primary purpose of clothing is to protect men from unfavorable atmospheric conditions. In this paper we are interested only in the thermal protection of clothing.

The thermal insulation value of clothing is not proveded by the fibre itself but by the dead air entrapped by it (25). Thus, by simple heat transfer rule of thumb, the thermal insulating value of clothing is proportional to the thickness of dead air enclosed.

An unit of heat resistance "clo" is used to measure the insulating value of clothes. It is defined as

$$1 \text{ 'clo'} = 0.88 \text{ hr-ft}^2\text{-F/Btu}$$

One 'clo' is about the insulation required for average men at 70°F air and wall temperature. Fig. 2 (26) shows the thermal insulating value for a narrow air spaces between two blackened horizontal plates with heat flow upward. The insulation at first increases linearly with the thickness but thus the slope decreases until a thickness of about ½" is reached. There is no more gain

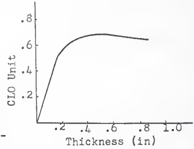

Fig. 2 Insulation of an air space between two plates vs. thickness of the space (26)

in insulation by making the space wider because of the increased development of convection currents. The value of 0.5 clo is about the maximum insulation obtainable by adding a single loose overall over a clothing ensemble (27).

However, this convection current can be prevented by filling the air space with loose material of low bulk density. Fig. 3 shows the results by Larose (28) which indicates that the thermal insulation is proportioned to thickness of the dead air space (solid line). The result of about 4.7 clo per inch of thickness is about the maximum that clothing could offer. It seems to be agreed on that 4 clo per inch is approximately the value achieved in practice (29) due to the following factors

i. air entrapped is not totally immobilized.

ii. heat transfer area increases by the effect of curvature.

When clothes are put on a body, the heat transfer area increases, this decreases the insulation of the clothing in two ways. First, it increases the heat loss from clothing surface to air per unit body surface since the heat loss is proportional to the area. A factor f_{clo} is, thus, introduced which is defined as the ratio of the surface area of the clothed body to surface area of the nude body measured by DuBois' method. Heat loss from clothing surface to the air can be expressed as

$$C = \frac{A_{Du}}{R_a} f_{clo} (t_{clo} - t_a) \frac{1}{.88} \quad (Btu/hr) \qquad (16)$$

Where

R_a = insulation of air (clo)

t_{clo} = temperature of the clothing surface area (F)

The effect is as though the insulation value of the air decreases by the amount of f_{clo}. Second, the conduction area of the dead air entrapped by the clothing increases, thus, increases the heat loss through the clothing. If the body is considered to be composed of cylinders, the heat loss through the dead air can be expressed as (30)

$$H = \frac{(t_i - t_o)\ 2\pi kl}{(r_o/r_b)} \qquad (Btu/hr) \qquad (17)$$

where

H = sensible heat loss from the body surface

k = conductivity of the air entrapped by clothing

r_o = radius of the outside clothing (ft)

l = length of the cylinder (ft)

f_b = radius of the cylinder (ft)

If r_o/r_b is less than 2, eq. 17 can be reduced with only slight error to (30)

$$H = \frac{1 \ + r_o/r_i}{2(r_o - r_i)} \ k \ A_i \Delta_t \qquad (Tru/hr) \qquad (18)$$

The dotted line in Fig. 3 shows the tctal curvature effect on insulation of the clothing. The detail of the

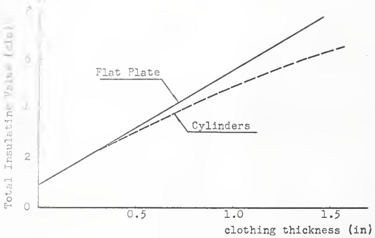

Fig. 3 Relation of the total insulation of clothing to the thickness of clothing at still air condition. (see App. 1)

calculation are given in Appendix II. The total insulating value is the insulating value of the air at this laboratory conditions (slow air motion) plus the insulation value of the dead air entrapped by the clothing.

Clothing and Comfort

Satisfactory comfort conditions for a person at rest or work depend upon the amount of clothing worn and the rate of work (or the rate of heat which it is necessary to be dissipated from the body). From Eqn. 1

$$M = \pm S \pm E \pm C \pm W \pm K$$

Where

K is small for a standing subject and can be neglected.

M depends upon the nature of activities and can be predicted by ref. (17).

W depends upon the rate of activities (see ref. 14).

S is approximately zero at thermally neutral conditions.

E depends on the rate of activities and humidity.

It is known that humidity has only a slight effect upon sedentary subjects under thermal comfort conditions as recorded by Nevins (12), and a relative humidity ranging of 25 to 65% caused no significant effect upon male comfort when the body activity levels are higher than sedentary under comfort conditions as pointed out by McNall et al (13).

Table 2 is few data points taken from refs. (12, 13, 17). For comfort, if M is fixed, E is fixed (about 42% of M). Neglecting humidity effects, the heat dissipated by convection and radiation is thus, fixed. With the aid of a basic heat transfer equation (31) the insulating value of clothing required to keep the body comfortable can be expressed by

$$\bar{R}'_{cl} = \frac{t_b - t_a}{(C + R)\ 0.88} A_{Du} \qquad \text{(clo)} \qquad (19)$$

To facilitate the calculation, Table 3 is developed. A constant sensible heat loss line vs. temperature difference at comfort is drawn in Fig. 4. Thus, for a fixed temperature difference and metabolic rate, the insulation of clothing

Table 3 Thermal Comfort Condition for Four Levels of Men's Activities

Activity Levels	1	2	3	4
(1) M (Btu/hr)	397	622	829	1061
E (Btu/hr)	(2) 168	(1) 294	(1) 373	(1) 462
R + C (Btu/hr)	229	328	456	599
(3) skin temp. (°F)	93.1	91.7	90.0	88.0
(4) comfort temp. (°F)	77.5	71.0	66.0	62.0

Level	Activities
1	seated at rest.
2	sitting, moderate arm and leg movements.
3	sitting, heavy arm and leg movement, lifting or pushing.
4	walking about, with moderate lifting or pushing.

(1) McNall et al "Metabolic Rates at Four Activity levels and their Relationship to Thermal Comfort."

(2) Assume the evaporation heat loss is 42% of total heat loss by reference (1).

(3) Fanger "Calculation of Thermal Comfort: Introduction of a Basic Comfort Equation" ASHRE Trans., 73, 1967 (Fig. 1).

(4) McNall et al "Thermal Comfort (Thermally Neutral) Conditions for Three Levels of Activity." ASHRAE Trans., 73, Part 1, 1967.

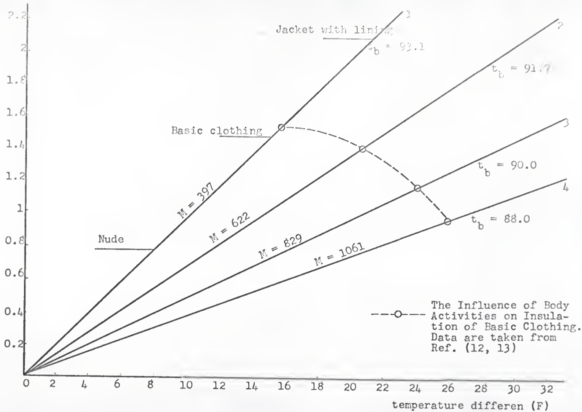

Fig. 4 The Amount of Clothing Required For Men's Comfort at Given Temperature Differences and Subject Activities

required to keep the body comfortable can be found in this chart. The total insulation value $\overline{R}'$ for nude, basic clothing (see App. IX) and a jacket with lining over the basic clothing are also drawn for comparison. It should be pointed out that the clo value is based on the low air movement (less than 30 ft/min) and a relatively motionless body. When a body is moving, a creation of both external and 'internal' air velocity is expected and as a result the insulation of air and clothing are lower than that obtained from a copper manikin test. It has been shown (32) that a typical U.S. army cold climate uniform possesses only about half as much insulation during walking as during quiet standing. In Fig. 4 a dotted line is drawn for the total insulation value of the basic clothing worn by the subjects in ref. (12, 13) and calculated by Eq. 19 with the assumption that the heat storage term S is zero during the experiment when the subject is in a comfort condition. This line shows the effect of body movement on the total insulation value of the basic clothing.

Additive effect of Mutilayer of Clothing

In determinating the insulation of clothing, it is noted that the heat loss is not uniform over the surface of the clothed body. For example, when a person wears a jacket over a basic clothing ensemble, the head and hands are bare, only a single layer covers the lower extremities while there are four layers (jacket, lining, shirt and underwear) on trunk.

To calculate the additive layer effect, the following assumptions are made:

1. The insulation of air is constant all over the body and clothing surface.
2. The insulation of each clothing layer is equal for each part of body surfaces if it is of the same materials.
3. The insulation of basic clothing ensemble is equal for each part of the body even though the items are of different materials.
4. The surface temperatures of the copper manikin are equal over the whole body.

To aid the calculations a 'heat circuit' is drawn in Fig. 5 for a subject with jacket (or lining, or jacket with lining). There are four different kinds of insulation for this subject and they are listed in Table 4. Then the total resistance of these parallel resistances is given by

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \qquad (1/\text{clo}) \qquad (20)$$

Thus, for each single jacket (or lining) the insulation R_t based on the area covered by it can be calculated if its insulation $\bar{R}'$ averaged on the whole body surface is known. This can be measured experimentally.

Table 4 Four Different Insulation for a Subject with Jacket and Lining

Parts	Area (%)		Insulations (Clo)	Heat Resistance
head & hands	A_h	.115	R_a	$R_1 = R_a/A_h$
legs & part of thigh	A_l	.360	$R_b' = R_b + R_a/f_{clo}$	$R_2 = R_b'/A_l$
trunk & part of thigh	A_t	.376	$R_t' = R_t + R_b + R_a/f_{cl}$	$R_3 = R_t'/A_t$
sleeves	A_s	.149	$R_s' = R_s + R_b + R_a/f_{cl}$	$R_4 = R_s'/A_s$
Total, average on the body	A_{Du}	1.000	$\overline{R}'$	$R' = \overline{R}'/A_{Du}$

Where

R_a = insulation of air (Clo)

R_b = insulation of basic clothing based on the area covered by it (Clo)

R_t = insulation of the test jacket (or lining) based on the area covered by it (Clo)

R_s = insulation of the jacket sleeves based on the area covered by it (Clo)

R' = total insulation value on the body

$\overline{R}$ = the insulation value averages on the whole body area as a result on the test.

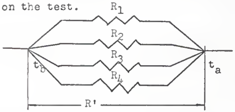

Fig. 5 An electric similarity of heat loss from body surface.

The multilayers of clothing based on the area they covered could be expected to be the sum of the insulation value of each layer of clothing if the air entrapped in each clothing layer remains same as though they were not combined. Thus, the insulation of the multilayers based on the whole body surface can be calculated by Eqn. 20. However, when adding a layer on the body some crushing will also occur, and the total insulation will be somewhat less than the sum of the individual articles.

CHAPTER III

PROCEDURE OF THE EXPERIMENTS

All tests were conducted in room 230 A, Justin Hall at Kansas State University. A conditioned laboratory of temperature 70 ± 1 F and 65 ± 2 per cent relative humidity was used for testing. An air movement profile of this laboratory indicated that there was an increase in air movement with the increase altitude and some fluctuation from location to location in the horizontal direction. However, at no point in the room did the air velocity exceed 30 ft per minute.

All clothing was allowed to reach equilibrium with the standard condition environment before any measurements were taken.

The start-up procedure, test procedure, dress procedure are discussed in reference (32).

Some corrections for the experimental results

1. A correction chart (Fig. A-1) was made for power input reading on the strip chart which indicates ± 2% error on the power reading. (For a detailed explanation, see Appendix 2).

2. A wall temperature correction and the radiation heat transfer between copper manikin surface and the experimentalist correction are made. An equivelent of 1.00 F is added to air temperature for this correction. (For a detailed calculation, see Appendix 3).

The above correction was applied through out the whole experiment. The assumption that air temperature equals wall temperature will result in as much as 100% error in the low temperature difference range if the correction was not applied.

Calculation on the Test Observation

The total insulation value of the test clothing (or air, if nude) is calculated according to the expression:

$$\bar{R}' = \frac{11.6\ (t_b - t_a)}{P} \quad \text{(clo)} \qquad (21)$$

where

P = power required for the copper manikin to maintain the temperature difference (Watt). It is read directly from a strip chart, and if the reading is varying with time, an average reading is taken during the time taking the 19 points of thermocouple reading.

t_a = the average of three thermocouples reading in the air at the back of the manikin's head, hip and foot positions and 6" from the back.

t_b = the average temperature of the surface of the manikin. (C)

Calculation of the body surface temperature (t_b)

The manikin is fitted with sixteen thermocouples (TC). Their positions are illustrated in Fig. 6. A potentiometer is used to determine the electromotive force generated by the thermocouples.

The simplest way of calculating the average surface temperature is a linear average of the 16 TC reading. However, there are three TC on the hands while it possesses only 5.6% of total area and there are 4 TC on lower extremities while they possess 41.7% of total area (see Fig. 6). It is seen that a linear average of 16 TC weighs too much on the temperature of hands and feet and too little on lower extremities and trunk.

A more accurate way of calculating the average skin temperature is to divide body surface into sections and take the temperature samples in each section. Then weight the average temperature in each section by its area. The following explains the procedure used.

Divide body surface into head, hands, upper extremities, lower extremities and trunk. The area of each part were measured by DuBois' (34) method. Then, the temperature obtained by a linear average of each section is weighted by their areas. Table 5 shows this method of calculation of the average surface temperature.

The comparison of these two methods are plotted in Fig. 7 for the total insulation $\overline{R'}$ of air, basic clothing (see App. 4)

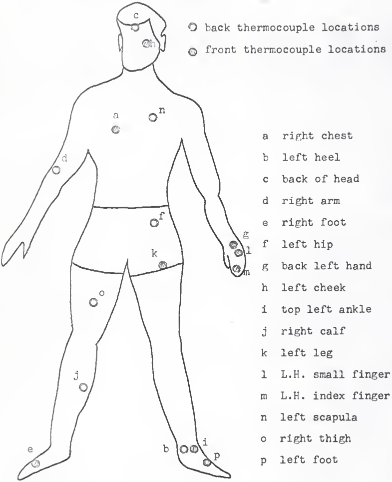

Fig. 6 Thermocouple Locations on Copper Manikin Surface

Table 5 Calculation of the 'weighted' surface temperature

Sections	(1) area (%)	(2) ave. temp.	(1)X(2) weighted
head	6.8	1/2(c + h)	
hands	4.7	1/2(l + m)	
lower ext.	41.1	1/5(k + o + j + i + p)	
upper ext.	15.0	1/3(d + d + g)	
trunk	31.8	1/3(a + n + f)	
		sum	C

and a jacket with lining. The solid line is the insulation value calculated by the linear average method and dotted line is by 'weighted' average method. When the copper manikin is nude, the clo value calculated from linear average method is 3.5% higher than that from 'weighted' average method because the hands and feet, which have seven of the sixteen thermocouples, possess only 12.7% of the total area of the body surface. When the body is clothed with basic clothes or jacket the effect is reversed; the clo values calculated by 'weighted' average method are 5.6% and 5.9% respectively higher than calculated by linear average method because the temperature of hands and feet are then lower than the average skin temperature.

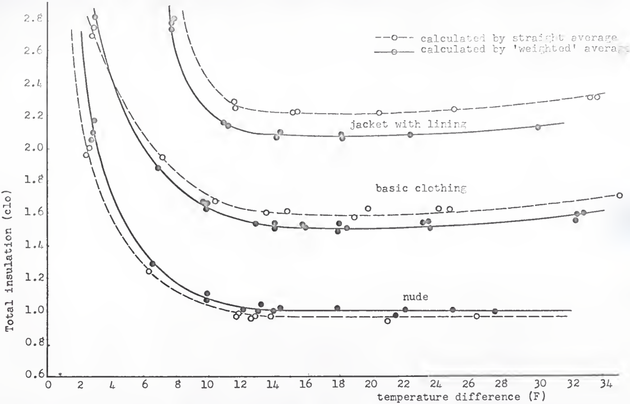

Fig. 7 The comparison between total insulation $\overline{R}'$ calculated by straight average of thermocouples and the area weighted average of the thermocouples (assuming wall temp. equal to air temp.)

CHAPTER IV

RESULTS AND DISCUSSION

Air Insulation on Copper Manikin

The tests on air insulation were done on the unclothed copper manikin. By varying the surface temperature of manikin, the temperature difference between it and the ambient was varied. Fig. 8 shows the insulation of air in clo as a function of temperature difference between the ambient air and manikin surface. For each temperature difference, the convective heat transfer C can be calculated by subtracting the radiation heat loss R given by Eqn. 3 from the manikin surface from total heat loss. Thus, the coefficient of convective heat transfer h_c can be calculated at each temperature difference by Eqn. 4. The results were plotted in Fig. 9. The theoretical curves recommended by McNall (20) and Fanger (17) were also plotted in this figure. At temperature differences between 0 and 12 F, the experimental data followed closely the curve recommended by ref. 20 and for temperature differences greater than 12 F, instead of increasing, h_c decreased unexpectedly. This was probably due to:

1. Thermocouple error due to the radiation heat exchange between the air temperature thermocouple junctions and the manikin surface. As a result the air temperature reading will be higher than the actual air temperature, and consiquently the calculated coefficient of convective heat transfer will

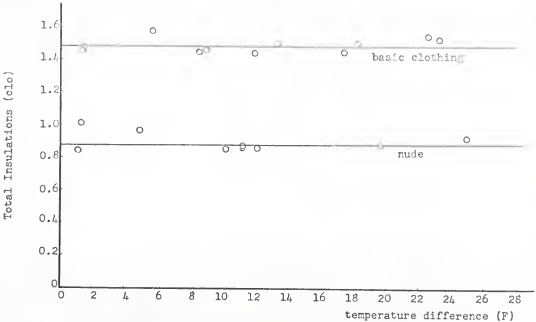

Fig. 8 The Total Insulation for Air and Basic Clothing (Clo)

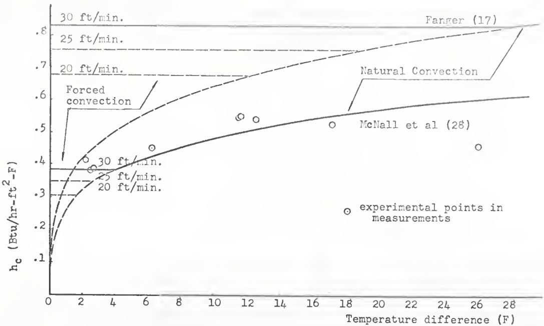

Fig. 9 Coefficient of Convective Heat Transfer h_c of Air with Low Air Velocities

increase with the increase of the temperature difference between air and the manikin.

2. Fluctuation in wall temperature which was measured once during the experiments and is not accurately known for all conditions.

3. Inaccuracies in estimating emissivity of the manikin surface and A_{eff} due to the lack in accurate data.

4. Instability in the automatic temperature control device especially at the high temperature differences.

The additive effect of clothing ensemble

The experiments were conducted under the same conditions as mentioned above. The set point temperature for each experiment was set to 34°C and 36°C such that the temperature differences for each experiment was about 8°C and 10°C respectively. The experiments were done on the following ensembles:

1. basic clothing (see App. 4)
2. basic clothing + single ply jacket (No. 9)
3. basic clothing + double ply jacket (No. 7)
4. basic clothing + corduroy shell (co.)
5. basic clothing + light lining (L. L.)
6. basic clothing + medium lining (M. L.)
7. basic clothing + heavy lining (H. L.)

the following are some of the above combinations, all are with basic clothing

8. No. 9 + L. L.

9. No. 7 + H. L.

10. Co. + H. L.

11. No. 7 + M. L.

12. (No. 7 + H. L.) + L. L.

13. (No. 7 + M. L.) + L. L.

14. No. 7 + No. 9

15. No. 7 + Co.

16. (No. 7 + M. L.) + (Co. + H. L.)

17. (No. 7 + M. L.) + (No. 9 + L. L.)

18. (No. 9 + L. L.) + (Co. + H. L.)

19. L. L. + H. L.

20. L. L. + M. L.

21. L. L. + M. L. + H. L.

It is found that insulation of air at low air velocity (less than 30 ft/min) is rather constant with the temperature differences, except on the very low temperature difference range where insulation of air increases as temperature difference decreases. However, within the practical range in these experiments, insulation of air can be assumed constant (.89 clo).

Fig. 8 shows the results of the experiments on basic clothing. The total insulation of basic clothing is quite constant (about 1.49 clo) except on very low temperature difference range, as seen in this figure. Its insulation is $\bar{R}' - R_a/f_{clo} = 0.68$ clo by assuming $f_{clo} = 1.1$ (compared with

0.6 recorded in the previous works (33, 34) calculated by linear average of 16 thermocouples on the manikin surface as the body average surface temp.).

The rest of the experiments were shown on Table 6 and Table 7. Table 6 is for a single layer over the basic clothing (2 to 7) and the insulation based on the body surface covered by it (R_3) was calculated and listed on the same Table. For the combination of two, three or four layers of clothing the total insulation $\bar{R}$ resulting from these experiments was listed on Table 7 (8 - 21). The theoretical predictions showed an excellent agreement with the experimental results, and only 0.5% to 4.0% difference were recorded. This small discripancy between the theoretical sum of the insulation values of the ensembles as predicted by Eqn. 20 and the experimental results shows that the individual insulation of clothing will not be affected significantly by adding successive articles of clothing. However, the loss of 0.5 to 4.0% insulation value for adding articles of clothing shows that the additional pressure did compressed the air layers entrapped by the clothing somewhat and thus, decreased the insulation of each air layer.

The variety of combinations of different jackets and lining provides sufficient data to support the above statements for light clothing. Arctic-type heavy clothing may show a more significant loss in insulation due to "layering."

Table 6 The total insulation of single jacket or lining on basic clothing ($\bar{R}'$) resulting from experiments and the calculated insulation value R_t' based on the surface covered by it. (by eq. 20)

Clothing	$\bar{R}$	$1/R_2$	$1/R_1$	$1/R_4$	A_t	R_3	f_{cl}	R_a/f_{cl}	R_t
No. 9	1.83	$\frac{0.36^*}{1.64}$	$\frac{0.115}{0.89}$	$\frac{0.149}{3.5}$	.376	2.38	1.20	.74	.80
No. 7	1.90	=.242	=.129	=.043		2.74			1.16
Co.	1.89					2.61			1.03
L. L.	1.79	$\frac{0.51}{1.64}$	$\frac{0.115}{0.89}$		.376	3.14	1.27	.70	1.61
M. L.	1.74	=.312	=.129	0		2.78			1.25
H. L.	1.84					3.62			2.08

Where

$\bar{R}$ = experimental results on the total insulation averaged on the body surface (Clo)

R_t = the insulation of the tested clothing based on the area covered by this clothing and calculated by eq. 20.

$R_1 = R_a/A_h$ = heat resistance on hands and head weighted by areas.

$R_2 = R_b'/A_1$ = area weighted total heat resistance on the parts covered by the basic clothing and not covered the tested clothing

$R_3 = R_t'/A_t$ = area weighted total heat resistance on the parts covered by the tested clothing (except on sleeves)

$R_4 = R_s'/A_s$ = area weighted total heat resistance on the parts of sleeves

R_a = insulation of air, 0.89 in this case

*1.64 is the total insulation value of the basic clothing based on the area covered by it.

Table 7 The experimental results of clothing ensemble compared with the theoretical predicting by eq. 20

Clothing	R_t	R_a/f_{cl}	R_t'	$1/R_3$	$1/R_1$	$1/R_2$
No. 9 + L. L.	2.41	.74	3.99	.094	$\frac{0.115}{0.89}$	$\frac{0.36}{1.64}$
No. 7 + H. L.	3.14		4.72	.079	=.129	=.22
Co. + H. L.	3.11		4.69	.080		
No. 7 + M. L.	2.41		3.99	.094		
(No. 7 + H. L.) + L. L.	4.85	.74	6.43	.059	.129	.22
(No. 7 + M. L.) + L. L.	4.02		5.06	.067		
No. 7 + No. 9	1.96	.74	3.54	.106	.129	.22
No. 7 + Co.	2.19	.74	3.77	.100		
(No. 7 + M.L.)+(Co. + H.L.)	5.52	.74	7.10	.053	.129	.22
(No. 7 + M.L.)+(No.9+ L.L.)	5.82		7.40	.051		
(No. 9 + L.L.)+(Co. + H.L.)	5.52		7.10	.053		
L. L. + H. L.	3.69	.78	5.74	.071	.129	$\frac{0.509}{1.640}$
L. L. + M. L.	2.86		4.48	.084		=0.31
L. L. + M. L. + H. L.	4.94		6.56	.057		

Table 7 Concluded

Clothing	$1/R_4$	$\overline{R}'$ Calculate	$\overline{R}'$ experi.	erroe (%)
No. 9 + L. L.	$\frac{0.149}{3.50}$	2.06	2.05	-0.5
No. 7 + H. L.	=.043	2.12	2.07	-2.5
Co. + H. L.		2.12	2.10	-1.0
No. 7 + M. L.		2.06	2.04	-1.0
(No. 7 + H. L.) + L. L.	=.043	2.22	2.20	-0.9
(No. 7 + M. L.) + L. L.		2.18	2.15	-2.0
No. 7 + No. 9	$\frac{0.149}{5.420}$	2.07	2.06	-0.5
No. 7 + Co.	=.028	2.10	2.11	+0.5
(No.7 + M.L.)+(Co. + H.L.)	.028	2.32	2.30	-0.8
(No.7 + M.L.)+(No.9+ L.L.)		2.34	2.30	-1.7
(No.9 + L.L.)+(Co. + H.L.)		2.32	2.30	-0.8
L. L. + H. L.		1.96	1.88	-4.2
L. L. + M. L.	0	1.91	1.84	-2.7
L. L. + M. L. + H. L.		2.02	1.96	-4.1

ACKNOWLEDGEMENT

The author would like to express sincere gratitude and indebteness to Dr. McNall, his major professor, for suggesting the experiments, his untiring valuable suggestions, corrections and criticism toward the completion of this paper, inspite of a very busy schedule.

Also deserving acknowledgement are Dr. Azer, Mechanical Engineering Department, for his corrections of this paper and Miss McCracken, Clothing Department, for her help in providing some available data and experimental schedule.

The author wishes also to acknowledge the help of the Clothing Department of Kansas State University, for making available their conditioned room and equipments which made this experiment possible.

REFERENCES

1. American Society of Heating and Air-Conditioning Engineers, ASHVE Guide 1958 Chapter 6.

2. Newburgh, L.H. Physiology of Heat Regulation and the Science of Clothing WB. Saunders Company, 1949, p. 291-442.

3. Winslow, C.E.A. and Herrington, L.P., Temperature and Human Life Princeton University Press, Chapter 4, 1949.

4. Fahnestock, M.K. and Werden, J.E., Refrigerating Engineer 64, 43 (Feb. 1956).

5. Hick, F.K. et al "Physiological Adjustment of Clothed Human Being to Sudden Change in Environment - First Hot Moist & Later Comfortable Conditions" ASHAE, Transactions 58, 189 (1952).

6. Inouye, Tohru et al "A Comparison of Physiological Adjustment of Clothed Women and Men to Sudden Changes in Environment" ASHAE, Transactions 59, 35 (1953).

7. Yaglou, C.P. "A Method For Improving The Effective Temperature Index" ASHAE, Transactions 53, 307 (1947).

8. Yaglou, C.P. "Thermal Insulation of Clothing" ASHAE, Transactions 54, 291 (1948).

9. Belding, H. S. et al "Thermal Resposes and Efficiency of Sweating When Men are Dressed in Arctic Clothing and Exposed to Extreme Cold" American Journal of Physiology (April 1, 1947).

10. Rodwell, E. D. et al "An Investigation of the Physiological Value of Sorption Heat in Clothing Assemblies." Journal of the Textile Institute XVI T624 - T645.

11. Nevins "Criteria for Thermal Comfort" Building Research July Aug. 1966, 27 - 30.

12. Nevins et al "Temperature Humidity Chart for Thermal Comfort of Seated Persons" ASHRAE Journal Vol. 8, No. 4, April, 1966.

13. McNall et al "Thermal Comfort (Thermally Neutral) Conditions for Three Level of Activity" ASHRAE Transactions 1967.

14. American Society of Heating and Air-Conditioning Engineers, ASHVE Guide 1965 - 1966 p. 101-114.

15. Jacob, M. and Hawkins, G.A. Element of Heat Transfer N. Y. John Wiley and Son Inc., 1950.

16. Wiebelt, J.A. Engineering Radiation Heat Transfer Holt, Rinehart and Winston 1966, p. 54.

17. Fanger, "Calculation of Thermal Comfort; Introduction of A Basic Comfort Equation" ASHRAE Transaction, 1967.

18. Hardy, J.D. "Heat Transfer" Chapter 3. Physiology of Heat Regulation, Newburgh, Sounders Co., Philadelphia, 1964, p. 96.

19. Winslow, C.E.A., Herrington, L.P. & Gagge, A.P. "The Determination of Radiation and Convection Exchanges by Partitional Calorimetry" Am. J. Physiology 116; 669, 1936.

20. McNall and Sutton "Thermal Comfort and Comfort Equations for Heating Applications" Minneaplis-Honeywell Research Report No. Gr 1823-R2.

21. American Society of Heating and Air-Conditioning Engineers, ASHVE Guide 1949 p. 218, 223, 616, 618.

22. Nielsen and Pedersen "Studies on the Heat Loss by Radiation and Convection from the Clothed Human Body" Acta. Phsiol. Scand. 27, 1952, 272.

23. Inouye et al "Effect of Relative Humidity on Heat Loss of Men Exposed to Environments of 80, 76 and 72 F" ASHVE Transactions. 59, 1953, 329-346.

24. Belding & Hatch "Index for Evaluating Heat Stress in Terms of Resulting Physiological Strains" ASHVE Trans. 62, 1956 p. 213-236.

25. Burton, A.C. and Edholnn O.G. Man in A Cold Environment Edward Arnold Ltd. 1955.

26. Burton, A.C. "Insulation by Reflection and the Development of a reflecting Cloth" Nat. Res. Council, Canada Report No. c, 2464.

27. Burton, A.C. and Coles, R. C. "Note on the Nature of the Thermal Insulation Added to a Flying-Suit When a Coverall is Worn" Nat, Res. Council, Canada Report No. c. 2297.

28. Larose, P. "Variation in Thermal Insulation of Double Pile Fabrics with Thickness" Nat Res. Council, Canada Report c. 2460, 1943.

29. Siple and Cochran. See Conference of Principles of Environmental Stress on Soldiers, p. 14-17 Environmental Protection Section. Office of Quartermaster General, 25th August, 1944.

30. Frank Kreith Principles of Heat Transfer International Text Book Company 1965 p. 28.

31. Belding, H.S. "Protection Against Dry Cold" Office of the Quartermaster, General Environmental Protection Section. Report No. 155, 1949.

32. McCracken, D.M. "Thermal Insulation Value of Certain Layered Assemblages of Men's Wear" Master's Thesis Kansas State University 1967.

33. Jim Jaax "Copper Man Study" Institute for Environmental Research Kansas State University. 1967.

34. DuBois, E.F. Basal Metabolism in Health and Disease Lea & Febiger, 1936 p. 130.

APPENDIX I

Curvature Effect on Thermal Insulation Value of Clothing

Let us assume the human body is constructed of cylinders as indicated in Table A-1. The radius for each cylinder is taking the maximum diameter of the copper manikin at that part.

Table A-1 Representing the human body by a combination of cylinders to determine the curvature effect on clothing

Parts	Dia. (in)	Length (in)	Area (%)
Trunk	11.4	28	35.6
Upper ex.	3.3	26	19.2
Legs	6.3	32	45.2

The insulation value of the clothing for each part of the body can be calculated by Eqn. 17 at various insulating thicknesses. The results are shown in Table A-2.

Table A-2 The effect of curvature on the insulation value of clothing at various thicknesses.

Thickness of Clothing (in)	Trunk	Upper Extremities	Legs	Air	Total
0.5 R_{cl} (clo)	2.25	2.04	2.18	0.82	2.99
weighted	.80	.39	.98		
1.0 R_{cl} (clo)	4.32	3.61	4.06	0.77	4.84
weighted	1.54	.69	1.84		
1.5 R_{cl} (clo)	6.24	4.85	5.70	0.72	6.45
weighted	2.22	.93	2.58		

It is to be mentioned that it was found during testing the curvature effects on clothing, that the body can be simulated by a cylinder with 6.3 in. in diameter and only slight error will result by this simplification.

APPENDIX II

CORRECTIONS FOR INSTRUMENT ERRORS

A wattmeter and a potentiometer were used seperately to check the power output readings on the strip chart recorder. Both instruments showed that the scale deflection indicated in the strip chart gave a lower power output reading when scale deflection was less than 50% and a higher reading when it was greater than 50%. A colibration chart (Fig. A-1) was made to correct the power input readings on the strip chart which showed as much as $\pm 2.5\%$ error.

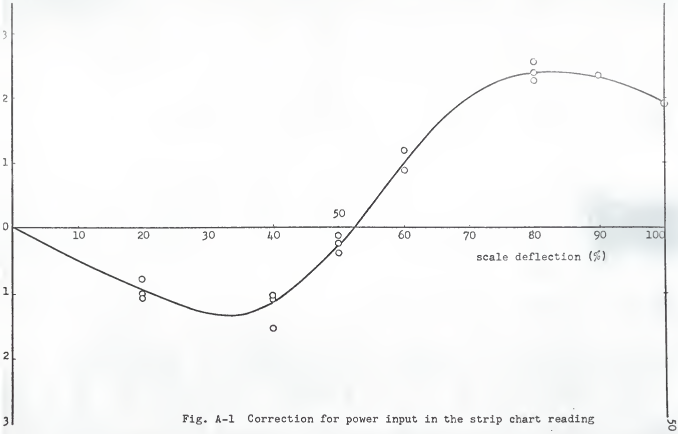

Fig. A-1 Correction for power input in the strip chart reading

APPENDIX III

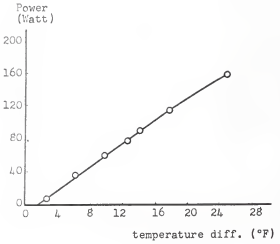

Fig. A-2 Copper Manikin Power vs. temperature diff. assuming air temperature equal to wall temperature

By McCracken (32)

A CORRECTIONS FOR MRT OF ENVIRONMENT NOT EQUAL TO AIR TEMPERATURE

Fig. A-3 is the power input required for manikin as a function of the temperature differences between manikin surface and air assuming that the MRT equals to air temperature. When the temperature difference equals 1.8 F the power required to keep the copper manikin in thermal equilibrium with the environment is zero. This must mean that the environment has an MRT higher than air temperature. A correction for this error is necessary.

The radiation heat exchange between experimental and manikin

The experimenter and the copper manikin were simulated as Fig. A-2. This assumption can be made because the area of the experimenter compared to wall is very small. The average temperature of the experimenter is 11°F higher than that of the wall temperature. Neglecting the end effect of the cylinder; the following view factors as given by ref. 16 are:

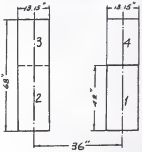

Fig. A-3 The simplified shape and relative position for the copper man and the experimenter.

$$F_{12} = 0.095/\pi \qquad F_{34} = 0.068/\pi \qquad F_{23\ 14} = 0.12/\pi$$

by reciprocity law

$(A_2 + A_3)F_{23\ 14} = A_2F_{21} + A_2F_{24} + A_3F_{31} + A_3F_{34}$

By special reciprocity law

$A_2F_{24} = A_3F_{31}$

$A_1F_{13} = \frac{1}{2}\left[(A_2 + A_3)A_{23\ 14} - A_2F_{21} - A_3F_{34}\right]$

$= 1.19/\pi\ (\pi r^2/144)$

$A_1F_{1\ 23} = A_1F_{12} + A_1F_{13} = 5.18/\ (\ r^2/144)$

$F_{1\ 23} = 0.124/\pi = 0.04$

Thus,

$$R = h_r(T_b - T_s)0.04 + h_r(T_b - T_w)0.96 \qquad \text{(A-1)}$$

since $T_s = 11 + T_w$

$$R = h_r\left[T_b - (T_w + 0.44)\right] \qquad (\text{Btu/hr-ft}^2)$$

where

h_r = radiation heat transfer coefficient

T_s = absolute mean radiation temp. (MRT) of the experimenter

T_w = absolute mean radiation temp. of the wall

T_b = absolute MRT of the manikin surface

<u>The radiation heat exchange between wall and manikin surface</u>

The average wall temperature was measured once. It was 71.55 F while the air temperature was 70 F. Thus T_w=T_a+1.55.

This result was not highly accurate since the wall temperature is a function of outside temperature and inside temperature. However, substituting this value of T_w into Eqn. A-1 yield

$$R = h_r [t_b - (t_a + 1.99)] \quad (\text{Btu/hr-ft}^2) \qquad \text{(A-2)}$$

If we roughly assume half of the heat loss is by radiation and half is by convection, then the total heat loss from the manikin surface will be

$$H = h/2 \{[t_b - (t_a + 1.99)] + (t_b - t_a)\} \qquad \text{(A-3)}$$

$$= h [t_b - (t_a - 1.00)] \quad (\text{Btu/hr-ft}^2) \qquad \text{(A-4)}$$

Thus, for calculating the insulation of clothing 1.00 F was added to the air temperature measured by three thermocouples to correct for MRT = t_a.

APPENDIX IV

BASIC CLOTHING

A complete description of the basic clothing ensemble for males is shown in Table A-2. Male undergarments were used during the tests with the copper man. The shirt tail was in and the neck open.

Table A-2 Basic Clothing Description

Clothing Description	Material	Weight (lb)
long sleeve shirt	100 % cotton	11.500 oz
trousers	100 % cotton	1 lb 3.250 oz
shorts	100 % cotton knit	3.500 oz
socks	100 % wool jersey filling	2.250 oz
Total		2 lb 4.500 oz

HEAT LOSS FROM HUMAN BODY AND INSULATION VALUE OF CLOTHING ENSEMBLE

by

HUNG CHEUNG LEUNG

B. Sc., Chu Hai College, 1964

AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1968

Based on the previous works on copper manikin, more advanced studies were done and some corrections for both instruments and wall temperature were found necessary. A method of area-weighted average manikin surface temperature was established and employed to determine the thermal insulation of clothing sets.

The experiments were conducted in a conditioned room with 70 $\pm$ 1 F air temperature and 65 $\pm$ 2% relative humidity. The wall temperature was slightly higher than air temperature and air velocity was below 30 ft. per min. The convection heat transfer coefficients were then calculated and they checked the theory quite well for temperature differences below 12 F. Deviations were found when the temperature difference was greater than 12 F. These were probably caused by thermocouple errors due to radiation heat exchange between copper manikin and thermocouple junctions.

A method of predicting the total insulation of a clothing ensemble from each component's insulation was found. The results were in excellent agreement with that from these experiments. A small but significantly lower result from the theoretical predictions were recorded due to the pressure from additional clothing layers in an ensemble.

From a literature survey, the effect of body movement on the total insulating value of clothing was found. This was shown on a thermal comfort chart which plotted the relations of effective environmental temperature, body activity levels and clothing insulation versus human comfort.